Lost in Translation: A Study of Bugs Introduced by Large Language Models while Translating Code

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Work done as part of IBM-Illinois Discovery Accelerator Institute (IIDAI)

[Ψ]*Work done when **Ali** was an intern at IBM Research*

Leaderboard: codetlingua.github.io

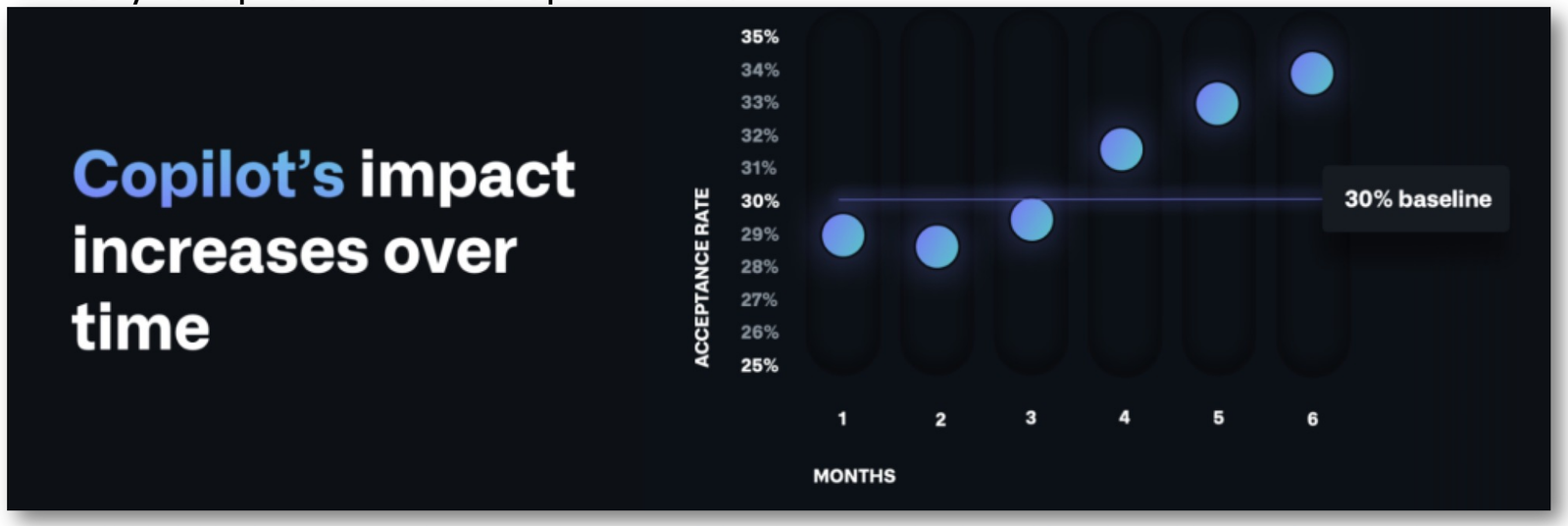
INTELLIGENT Code Analysis Testing

[*]Equal Contribution

LLMs for Code Generation & Understanding

- LLMs are used for assisting developers
  - **2021 & 2022:** Codex, CodeT5, GitHub Copilot, AlphaCode, etc.
  - **2023 & 2024:** GPT-4, Gemini, CodeLlama, Claude 3, etc.

Today, GitHub Copilot has been activated by more than one million developers and adopted by over 20,000 organizations. It has generated over three billion accepted lines of code, and is the world's most widely adopted AI developer tool.



https://github.blog/2023-06-27-the-economic-impact-of-the-ai-powered-developer-lifecycle-and-lessons-from-github-copilot/

What is Code Translation?

Code translation converts source code from one programming language to another

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Java Code

```java
public class Main {
    public static void main(String[] args) {
        int max = 5;
        for (int i = 0; i < max; i++) {
            System.out.println(i);
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Python Code

```python
max = 5
for i in range(max):
    print(i)
```

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❖ Use cases of code translation:

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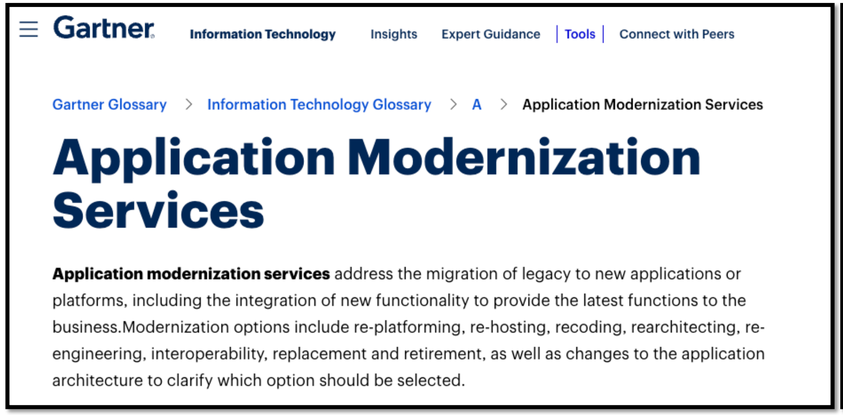
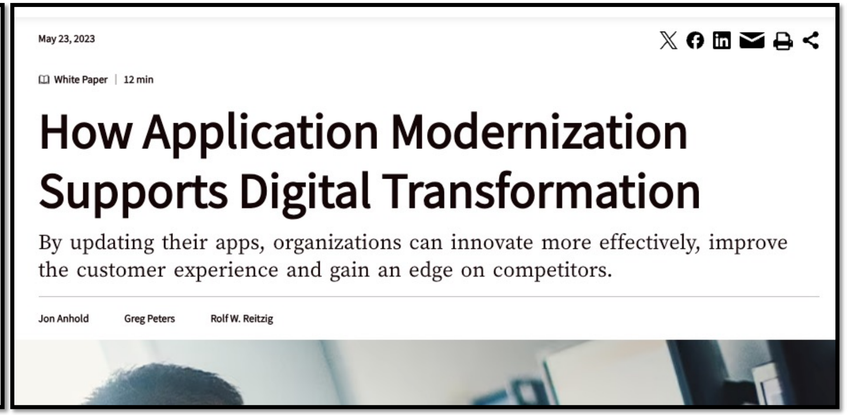
- Use cases of code translation:
  - Application modernization
  - Migrating legacy software to cloud-native applications





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  - LLMs **`generalizes`** well and generates more **`natural code`**

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- Code translation is challenging as it requires understanding both syntax and semantics
  - Transpiler techniques, e.g., C2Rust, CxGO, Java2C#
  - LLMs **generalizes** well and generates more **natural code**
- Existing learning-based techniques use small models (**<1B** parameter) and fail to achieve high accuracy

An Empirical Study on LLM-based Code Translation

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- Mitigating translation bugs

Empirical Setup

❖ Subject LLMs:

- We aim at using models **<20B** parameters due to compute constraints
- SOTA LLMs at the time of study

Modality	**Code**			**Text**			
Subject LLMs	CodeGen	CodeGeeX	StarCoder	GPT-4	Llama 2	TB-Airoboros	TB-Vicuna
Size	16B	13B	15.5B	-	13B	13B	13B
Context Window	2,048	2,048	2,048	8,192	4,096	2,048	2,048
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❖ Subject PLs:

- TIOBE Score[1], different paradigms, and availability of datasets
- C, C++, Go, Java, Python

[1] https://www.tiobe.com/tiobe-index/

Effectiveness of LLMs in Code Translation

Crafted benchmark datasets and real-life projects

Dataset	Source Language	Source Samples	# Tests	Target Language	#Translations
CodeNet[1]	C	200	200	C++,Go,Java,Python	800
	C++	200	200	C,Go,Java,Python	800
	Go	200	200	C,C++,Java,Python	800
	Java	200	200	C,C++,Go,Python	800
	Python	200	200	C,C++,Go,Java	800
Total / Average (CodeNet)	-	1,000	1,000	-	4,000
AVATAR[2]	Java	249	6,255	C,C++,Go,Python	996
	Python	250		C,C++,Go,Java	1,000
Total / Average (AVATAR)	-	499	6,255	-	1,996
Evalplus[3]	Python	164	2,682	Java	164
Commons-CLI[4]	Java	22	310	Python	22
Click[5]	Python	15	611	Java	15
Total / Average (All)	-	1,700	10,858	-	6,197

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	Go	14.3%	5.9%	42.0%	85.5%	16.9%	6.6%	0.9%
	Java	21.3%	10.3%	30.3%	81.3%	13.9%	6.5%	0.1%
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Total / Average (CodeNet)	-	18.1%	8.4%	37.3%	82.0%	13.2%	9.3%	2.0%
AVATAR	Java	8.1%	1.8%	11.9%	70.8%	1.8%	5.0%	0.0%
	Python	3.8%	1.6%	14.2%	52.2%	4.7%	0.9%	0.9%
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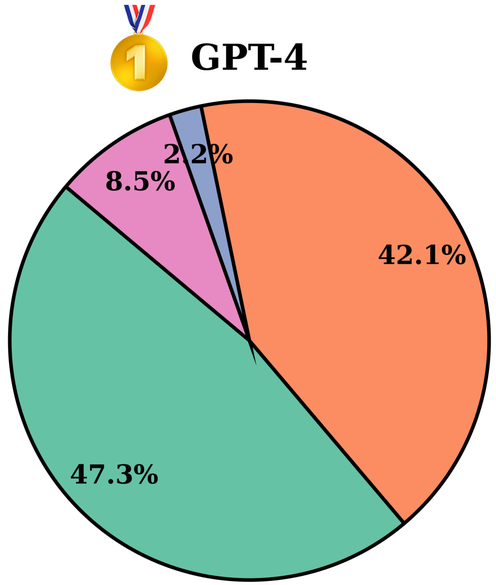

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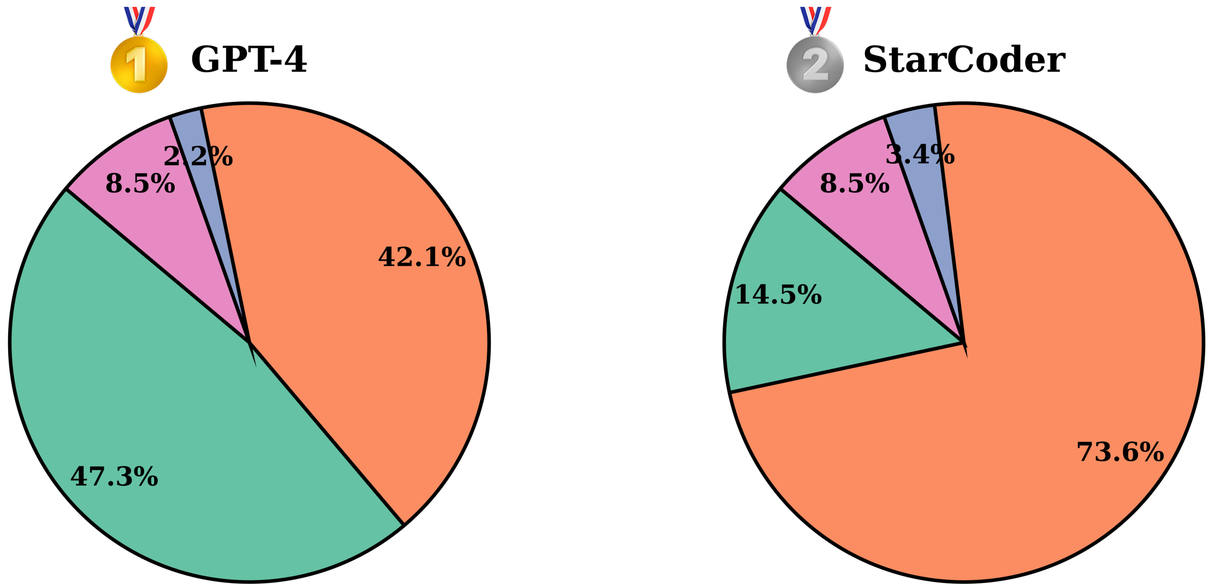

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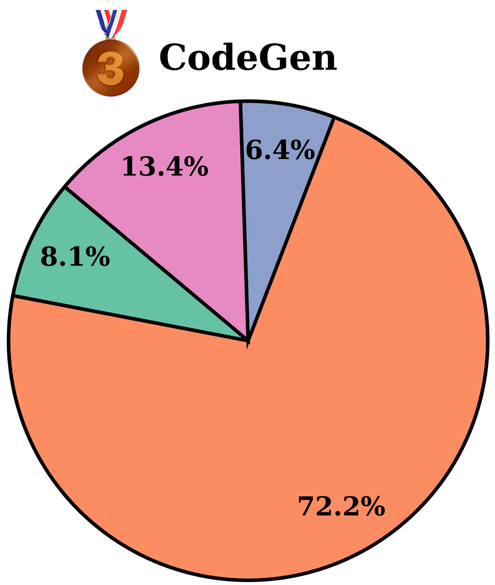

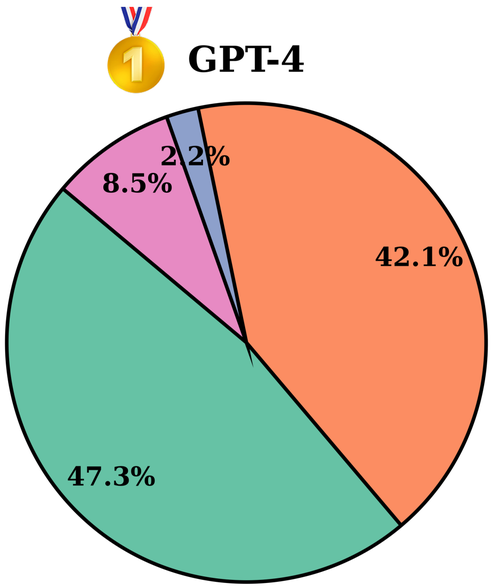

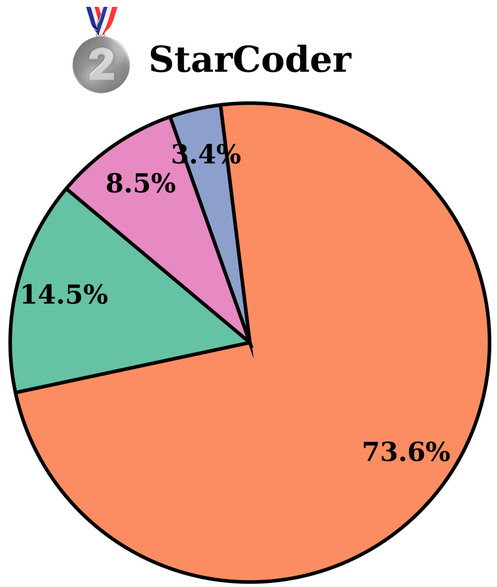

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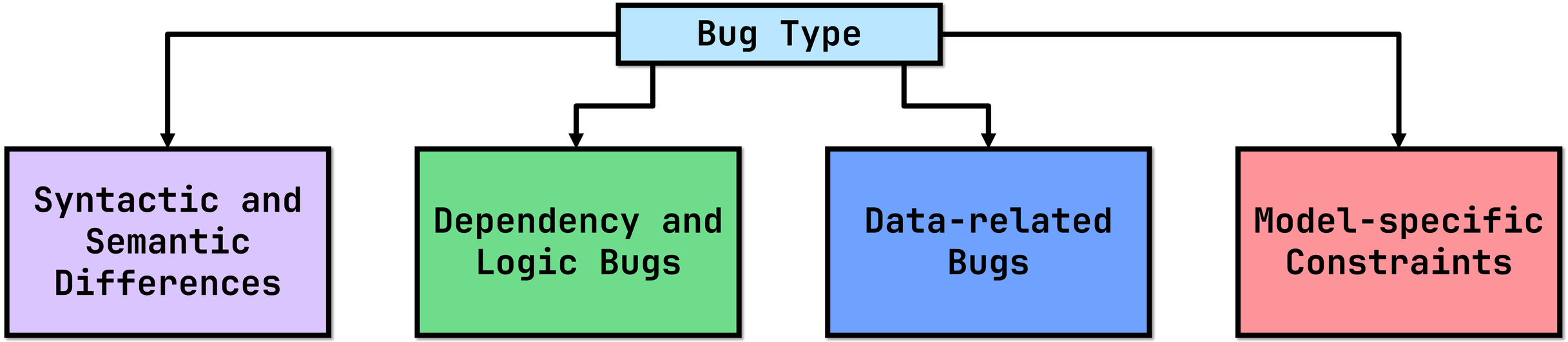
  - **8** human labelers (industry researchers and software engineers): **630** person-hours
  - **15** unique categories of translation bugs (details in paper)

Taxonomy of Translation Bugs

- We manually investigated and root caused **1,748** unsuccessful translations from the best performing model (GPT-4)
  - **8** human labelers (industry researchers and software engineers): **630** person-hours
  - **15** unique categories of translation bugs (details in paper)



Syntactic and Semantic Differences b/w PLs

LLMs fail to properly handle syntactic and semantic differences between PLs

Duplicating source syntax to target language

```
constant ld PI = atan2l(0, -1); # Original C++ code
PI = atan2l(0, -1)              # Incorrect Go code
```

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constant ld PI = atan2l(0, -1); # Original C++ code
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```

🚨 **atan2l is not available in target language (Go)** 🚨

Dependency and Logic Bugs

These bugs pertain to incorrect dependencies and logic of translated code

Missing library imports and definitions

```
void solve(){...}                  # Original C++ code
signed main(){...solve();}         # Incorrect Go code
```

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void solve(){...}                  # Original C++ code
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🚨 **solve() is called but not implemented in Go** 🚨

Data-related Bugs

LLMs suffer translating code which reads and writes data to stdin / stdout

Output Formatting

```
System.out.print("H"); System.out.println(Y - 1); # Java code
print("H", Y - 1)                                  # Python code
```

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```

🚨 **extra space added in Python output** 🚨

Translation Bugs in Real-World Projects

🚨**WE ARE THE FIRST EVER TO TRANSLATE AND INVESTIGATE REAL-WORLD PROJECTS**🚨

Real-world applications pose more complex challenges for code translation, such as handling method overloading, exceptions, inheritance relations, etc.

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Source Code (Java)

```java
public Options addOption(final Option opt) { ... }
public Options addOption(final String opt, final boolean hasArg,
                         final String desc) { ... }
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```

Translated Code (Python)

```python
def add_option(self, opt): ...
def add_option_arg(self, opt, hasArg, desc): ...
def add_option_desc(self, opt, desc): ...
```

Feedback-based Prompt Crafting

A technique for providing additional contextual information in the prompt to enhance LLMs’ responses

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Executing your generated code gives the following
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2. Provide incorrect translation and feedback (F)
3. Determine the objective and constraints (F)
4. A sample test I/O to further enrich the feedback (F)
5. Model-specific keyword (V)

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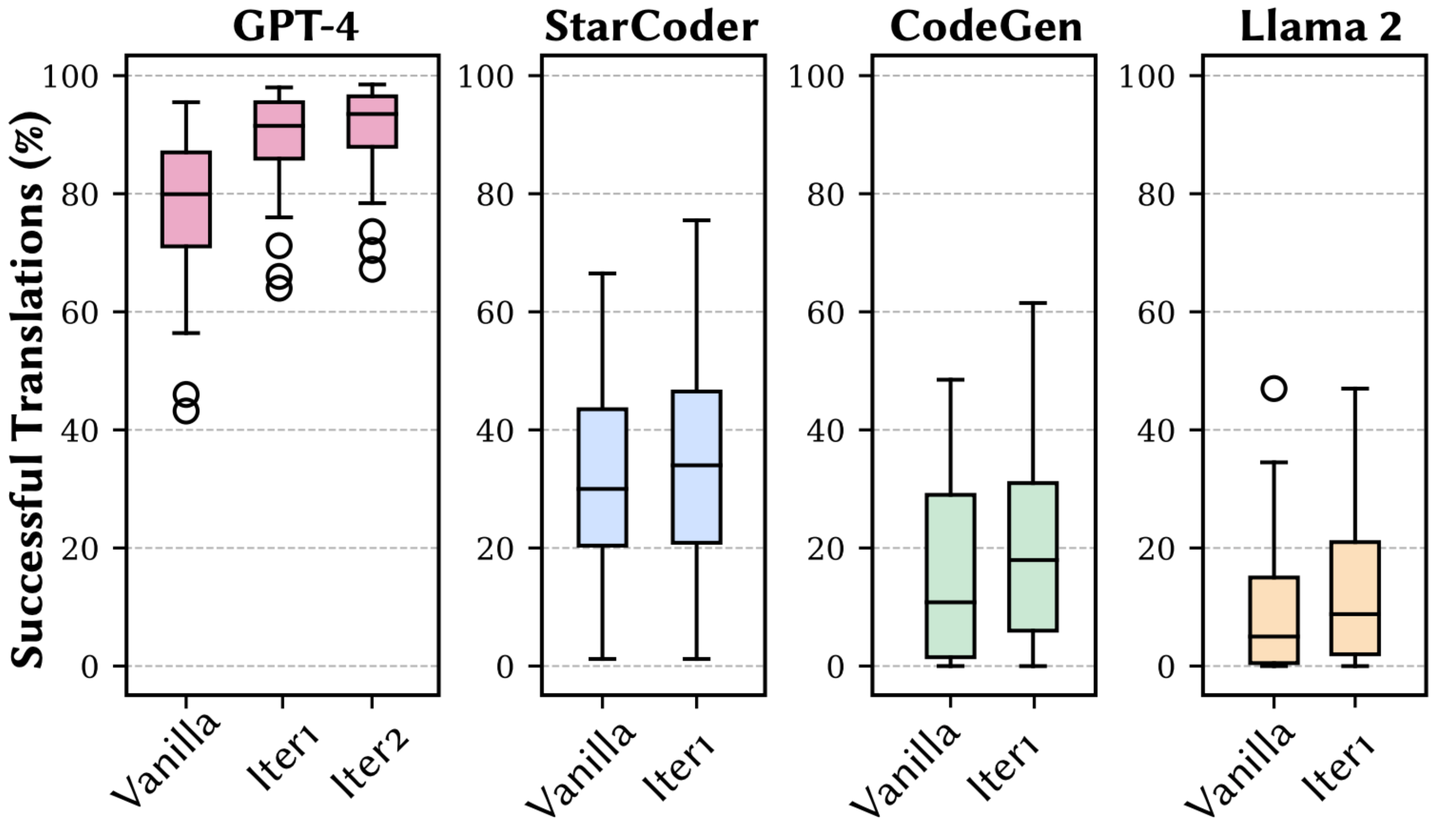

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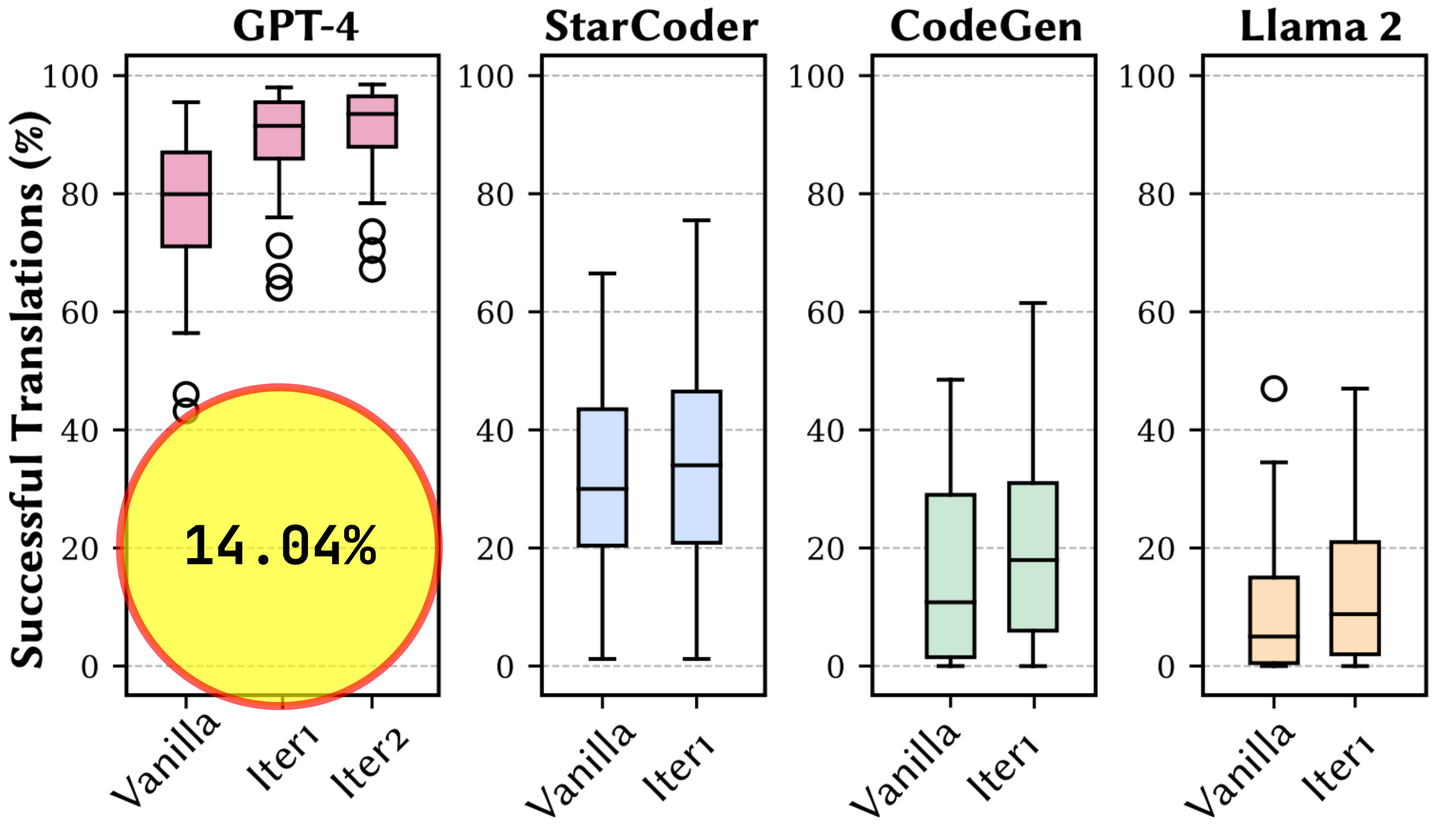

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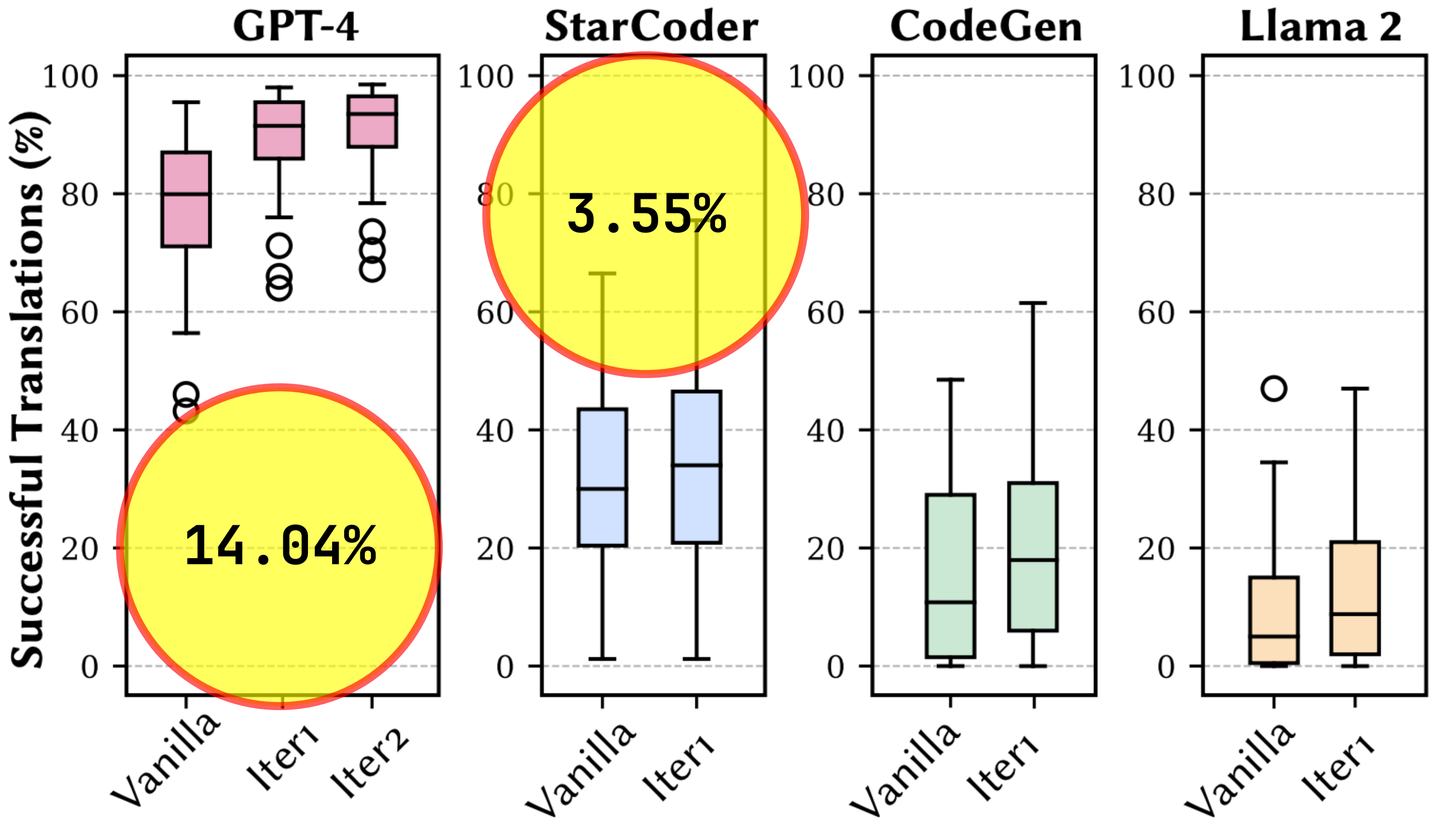

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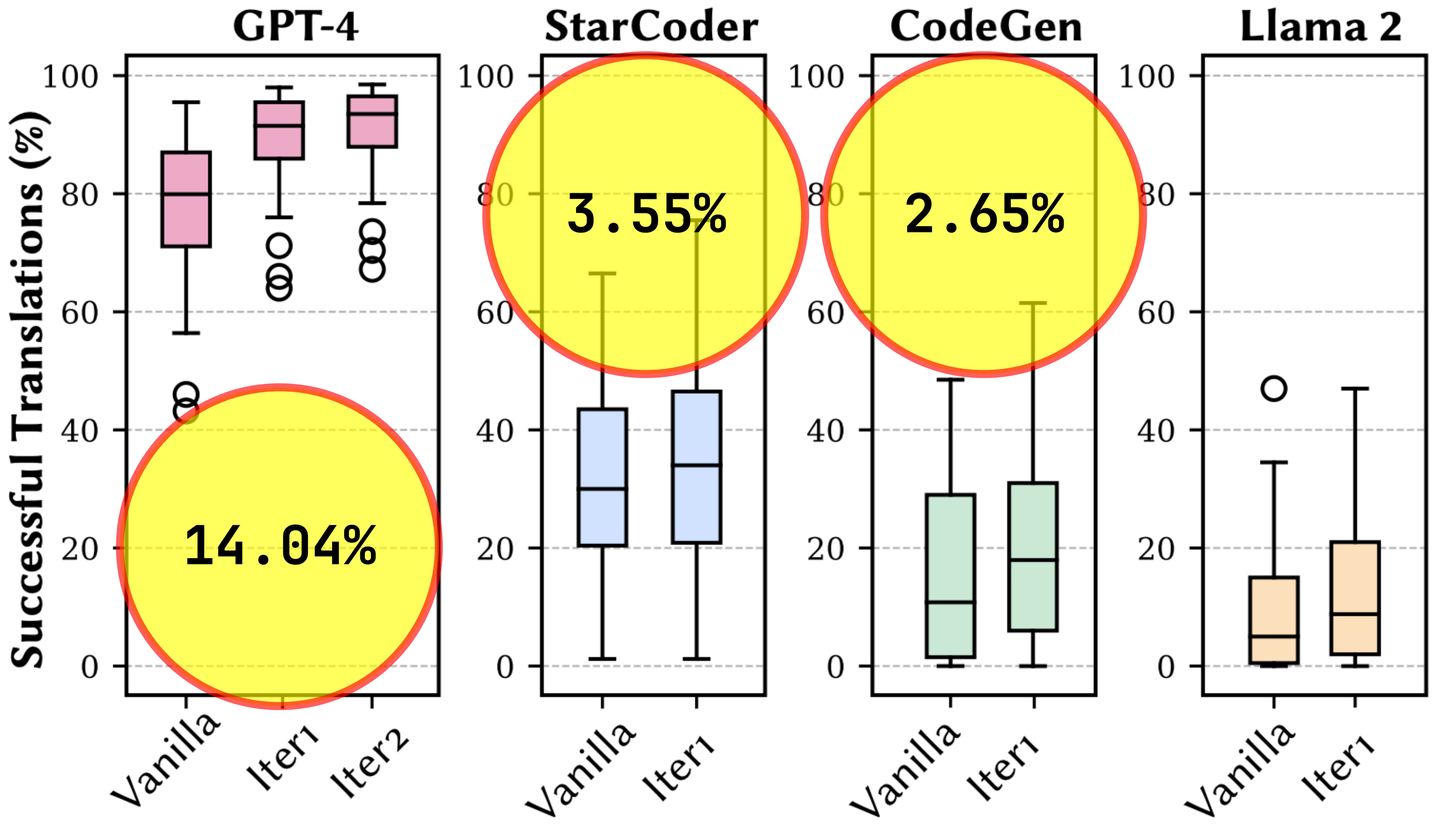

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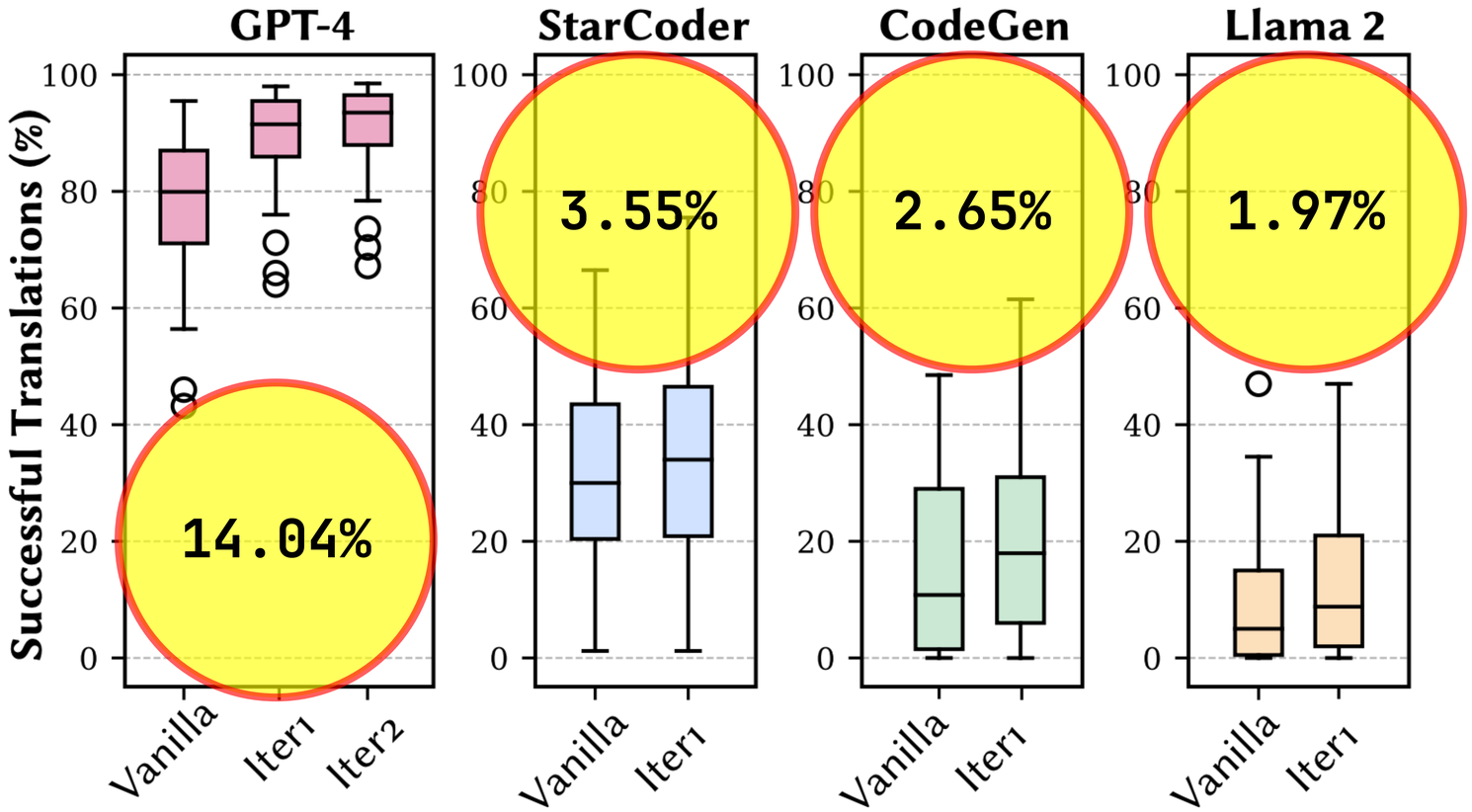

Comparison with non-LLM-based Techniques

Both approaches provide unique advantages, suggesting an ultimate solution can leverage both LLM and non-LLM (transpiler) techniques

Dataset	SL	TL	CxGO	C2Rust	Java2C#	CodeGen	CodeGeeX	StarCoder	GPT-4	Llama 2	TB-A	TB-V
CodeNet	C	Rust	-	**95.0%**	-	0.0%	0.0%	10.5%	61.0%	0.5%	0.5%	0.0%
	C	Go	62.3%	-	-	33.0%	0.0%	12.5%	**72.5%**	5.0%	5.5%	11.0%
	Java	C#	-	-	0.0%	0.5%	1.0%	26.5%	**49.0%**	1.5%	1.0%	4.0%
AVATAR	Java	C#	-	-	0.0%	0.0%	0.0%	10.4%	**59.2%**	2.0%	0.8%	0.4%

*{S, T} L: {Source, Target} Language, TB-{A, V}: TheBloke-{Airoboros, Vicuna}

Transpiler | **LLM**

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Transpilers 🤝 Language Models

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    let x: i32 = x.trim().parse().expect("Please type a number!");
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```

(a) C Code Translated to Rust by GPT-4

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#![allow(dead_code, mutable_transmutes, unused_assignments, unused_mut)]
extern "C" {                                                              1
    fn printf(_: *const libc::c_char, _: ...) -> libc::c_int;             2
    fn scanf(_: *const libc::c_char, _: ...) -> libc::c_int; }            2
unsafe fn main_0() -> libc::c_int {                                       3
    let mut x: libc::c_int = 0;                                           4
    let mut y: libc::c_int = 0;                                           4
    x = 0 as libc::c_int;
    y = 0 as libc::c_int;
    scanf(b"%d\0" as *const u8 as *const libc::c_char,                    5
          &mut x as *mut libc::c_int);                                    5
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(b) C Code Transpiled with C2Rust with annotations on safety issues.

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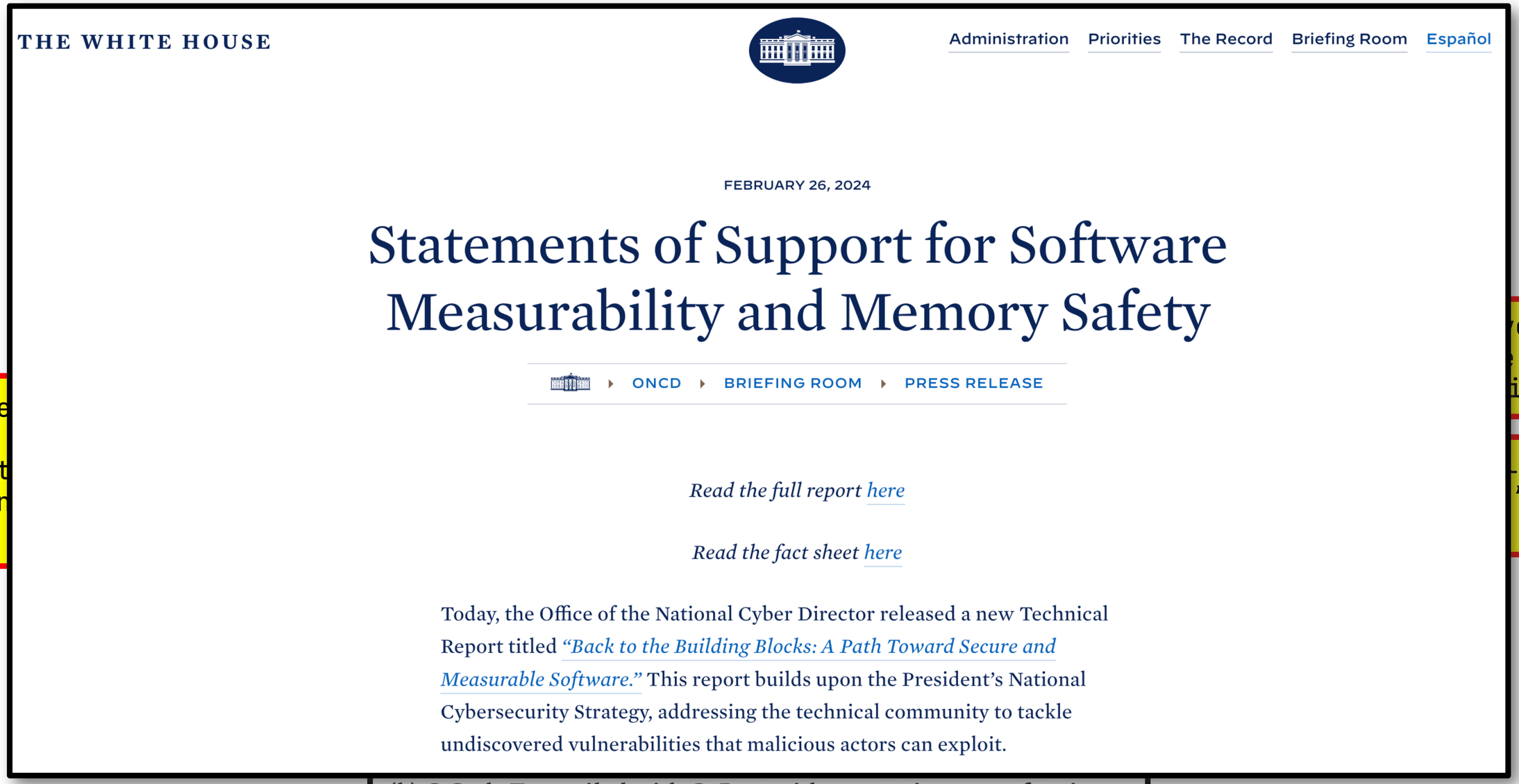
Usage of "unsafe block" circumvents Rust's safety checks

Unsafety of Transpilers

https://www.whitehouse.gov/oncd/briefing-room/2024/02/26/memory-safety-statements-of-support/



THE WHITE HOUSE

Administration Priorities The Record Briefing Room Español

FEBRUARY 26, 2024

Statements of Support for Software Measurability and Memory Safety

ONCD ▸ BRIEFING ROOM ▸ PRESS RELEASE

Read the full report here

Read the fact sheet here

Today, the Office of the National Cyber Director released a new Technical Report titled *"Back to the Building Blocks: A Path Toward Secure and Measurable Software."* This report builds upon the President's National Cybersecurity Strategy, addressing the technical community to tackle undiscovered vulnerabilities that malicious actors can exploit.

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Concluding Remarks

❖ We investigate the effectiveness of **7** LLMs across **5** datasets in code translation

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https://github.com/Intelligent-CAT-Lab/PLTranslationEmpirical

Please Check and Contribute to our Leaderboard

Leaderboard: codetlingua.github.io